Coefficient of Friction Measurement in the Presence of High Current Density

L. Brown and D. Xu
United States Naval Academy

K. Ravi-Chandar
The University of Texas at Austin

S. Satapathy
Institute for Advanced Technology, The University of Texas at Austin

Abstract—On the micro-scale, armature–rail interface contact is accomplished through surface asperity interaction. In this imperfect contact model (a version of the Bowden-Tabor model), we postulate the coexistence of one or more contact regimes, such as solid–solid contact, liquid–metal lubricated contact, and arcing contact. We are developing microscopic models and experimental apparatus to study this postulate. This work in particular describes the experimental apparatus developed to assist in the investigation of possible contact regimes and presents preliminary data that indicate a possible decrease in coefficient of friction in the presence of high current density when compared to a no-current condition.

I. INTRODUCTION

The real contact between rail and armature in a railgun is accomplished through surface asperity interaction on the microscopic scale. The relative motion brings asperities into contact and separation continuously as described in Bowden-Tabor model [2]. In the presence of current conduction through the asperities, continuous making and breaking of contact gives rise to the possibility of arcing, in addition to magnetic blow-off forces that tend to separate the contact. The situation is complicated in the presence of conducting vapor and liquid metal, which are likely products of friction and Joule heating in the interface. It is extremely difficult to probe the rail–armature interface directly to study tribological behavior. The apparatus described in this paper will help clarify some of the issues by enabling more controlled experiments. A mesoscale friction tester (MFT) was modified to allow the passage of direct current (dc) while simultaneously measuring the coefficient of friction and the parameters associated with current flow. Details of the construction and operation of the MFT are presented by Wang et al. [1]. The MFT is capable of performing friction studies with contact radii that range from 10 nm to 10 μm and contact forces from 10^{-6} to 10^{-3} N. This force scale is beyond that of an atomic force microscope (AFM) and an interfacial force microscope (IFM) but is below that of a surface force apparatus (SFA). Previously, significant work [2] has been conducted in the area of measuring coefficient of friction, but little information is available concerning the effects of current flow on

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE **2006**	2. REPORT TYPE	3. DATES COVERED **00-00-2006 to 00-00-2006**

4. TITLE AND SUBTITLE **Coefficient of Friction Measurement in the Presence of High Current Density**	5a. CONTRACT NUMBER 5b. GRANT NUMBER 5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)	5d. PROJECT NUMBER 5e. TASK NUMBER 5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **The University of Texas at Austin,Institute for Advanced Technology,Austin,TX,78712**	8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	10. SPONSOR/MONITOR’S ACRONYM(S) 11. SPONSOR/MONITOR’S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution unlimited

13. SUPPLEMENTARY NOTES
Presented at the 13th International Symposium on Electromagnetic Launch Technology (EML), Held May 22 - 25, 2006 in Potsdam, Brandenburg, Germany Copyright 2006 IEEE. Published in the Proceedings, http://emlsymposium.org/archive.html#

14. ABSTRACT

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**Same as Report (SAR)**	**8**	

the contact interface, particularly at the small-scale surface morphology (10^{-5} to 10^{-8} m) that might be found on electromagnetic (EM) launcher rails and armatures. An additional design parameter used in the apparatus modification was to create current densities that would approximate those found in an EML contact interface. Synergistically, the scaling factor for achieving resolution of the expected surface morphology forced small probe sizes, which simultaneously created conditions for the desired current density of approximately 10^{10} A/m^2, which is typical of the current density to be found in an EM launcher. The desire to investigate this particular regime of scale and current density motivated the modifications to be described in this work.

II. THEORY

A significant impediment to successful development of a multishot EM launcher is the cumulative degradation of rail surfaces at the armature–rail interface due to projectile launches. Little is known of the specific interaction mechanisms within this interfacial region, but tribological processes coupled with EM effects play a significant role. Development of a simulation model that somewhat describes the interfacial region between armature and rail has been an ongoing project at The University of Texas at Austin's Institute for Advanced Technology (IAT). To support model improvement, improved knowledge of the expected dynamic coefficient of friction between rail and armature is needed, particularly under conditions of high current density.

For determination of the current density, it was necessary to approximate contact spot size. Assuming that the contact areas between the probe and substrate metal sample remain elastic, it can be shown [3] that the Hertzian theoretical elastic contact spot size will be

$$a_0^3 = \frac{3\pi}{4}\left(k_1 + k_2\right)\left(\frac{R_1 R_2}{R_1 + R_2}\right) P_0 \tag{1}$$

where a_0 is the radius of the contact area, R_1 and R_2 are the respective radii of the contacting materials, P_0 is the applied force, and k_1 and k_2 are elastic constants of the materials, with

$$k_1 = \frac{1-\nu_1^2}{\pi E_1} \text{ and } k_2 = \frac{1-\nu_2^2}{\pi E_2}, \tag{2}$$

where ν is Poisson's ratio and E is Young's modulus of each material. In the case of this experimental work, R_2 will be assumed to be infinite as the specimen surface contacted by the probe is flat and the contact pressure is measurable using the MFT. We fixed R_1 by manufacturing contact probe tips with known radii of curvature via optical measurement using scanning electron microscopy (SEM).

Using the above methodology for determining contact spot size, for a steel-ball-tipped probe with R_1 = 0.22 mm in contact with a pure copper sample, the estimated radius of the contact spot was 0.75 μm. The experimentally desirable current density of approximately 1×10^{10} A/m^2 could then be readily achieved by supplying current from a benchtop power supply in the range of tenths of an ampere of output.

Rabinowicz [4] discusses measurement of the electrical resistance of an interface to enable study of the functioning of electrical contacts but goes no further than to offer simple equations for estimating contact size and the number of actual contact spots that are conducting. The modified MFT could possibly be used to further investigate this area.

III. APPARATUS

As mentioned previously, specific details of the apparatus construction can be found in [1]. Fig. 1 provides an overview of the apparatus.

In brief, a laser diode transmits a focused beam that impinges on a reflecting surface glued to the top surface of an elastic beam of known properties that is mounted, cantilever fashion, in a clamping device. Directly below the reflecting surface fixed to the top surface of the beam, a probe is mounted normal to the bottom surface of the beam. The probe is brought into contact with a conducting sample (typically fabricated from railgun component alloys) using a piezoelectric (PZT) stage that controls sample motion in three dimensions. The beam sensor will deflect and twist due to normal contact and lateral friction forces, respectively. The beam deflection is sensed when the reflected laser signal moves across the face of a position sensitive detector (PSD) mounted in the path of the laser signal downstream of the reflecting mirror mounted on the top of the sensor beam. The movement of the laser spot across the PSD is used to quantify the magnitude of the normal and lateral friction forces, enabling calculation of the coefficient of friction. The ratio of the lateral and normal forces is the friction coefficient. Fig. 2 shows the sensor beam and probe in contact with a polished copper sample.

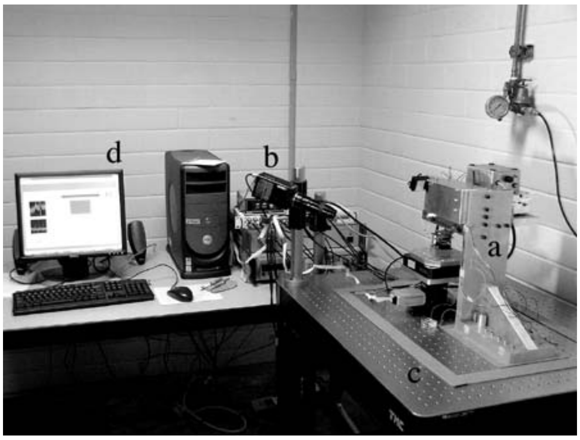

Fig. 1. Overview of the MFT with current-conduction capability: a) MFT, b) imaging camera, c) vibration isolation table, and d) data collection computer.

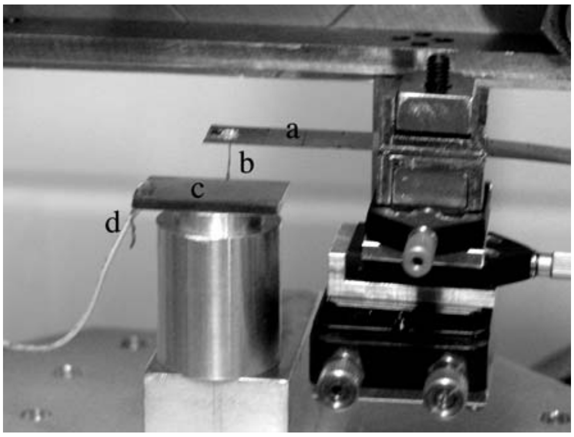

Fig. 2. a) Sensor beam with b) contact probe mounted above c) copper sample. d) Sensing lead is part of current conduction wiring harness.

The modification to the apparatus as described above dealt with supplying a potential across the sample and beam probe. To accomplish this modification, the following devices were used: a dc power supply, precision digital multimeter (DMM), and optical sensor. In brief, a power supply was connected via wiring harness to the beam and probe assembly and to the conducting sample. To this end, a Tectronix PS 280 dc power supply was used as the current source for experimentation. The power supply has two controlling modes—constant current and constant voltage. Constant current mode was selected as the controlling mode, because contact spot resistance would vary as contact pressure, spot size and sample materials were varied. The constant voltage feature was also used, by setting an upper limit of voltage potential at 10 V_{dc}. This upper limit prevented overdriving the data acquisition system, which is limited to a ± 10 V_{dc} input. Typical voltages seen when controlling in constant current mode of 0.02 A were less than 0.5 V_{dc}.

The determination of physical contact between the probe and sample surface is made by the evaluation of three parameters: optical evaluation of the status of contact, current flow between probe tip and sample surface, and beam deflection. Optical evaluation is the least accurate contact status parameter and is determined via a Panasonic model GP-KR222 industrial color CCD camera with attached Sony monitor. As the probe tip approached the sample surface, a reflection was seen on the monitor of the polished sample surface. The actual image and reflected image gradually approach contact when viewed in the monitor as the PZT stage is moved in the vertical direction and contact is assumed when the tips are seen to merge on the screen.

To assist in evaluating contact state using current flow, the apparatus was configured to measure three parameters associated with current flow. A shunt resistor was used to determine current flow; voltage drop across the probe tip to the sample surface was determined via measurement leads; and the presence of an arc flash was detected via a phototransistor. All three measurements were acquired by data collection software for further analysis and evaluation.

The second available parameter used to evaluate status of physical contact is that of the contact normal force. Contact is determined by an increase in the measured value for normal force voltage output from the sensor. This parameter is more sensitive than the optical method for determining contact but is subject to external influences such as vibrations from room traffic and ventilation and low-frequency vibrations from vehicular traffic.

Contact resistance is the final and most accurate parameter used for determining contact status. A Fluke 8522A digital multimeter selected to four-wire resistance mode is monitored to determine onset of contact. Four leads are connected across the contact interface, the probe and sample are brought into near contact by manually moving the support platform below the PZT stage, and final movement to contact is performed by stepping the PZT stage until a resistance value is read on the Fluke display. Simultaneous affirmation of contact is seen on the data collection display as normal force voltage slightly increases and spot location deflects a small amount.

A third parameter associated with measuring contact performance is that of the arc that develops when the probe tip is brought sufficiently close to the surface of the sample. An optical detector was fabricated from a photo detector, a length of fiber optic cable, and two variable potentiometers in series on the collector leg of the photo detector. The end of the fiber optic cable is placed in close proximity to the probe tip, and as the tip is brought near the surface of the sample, at a certain distance, the applied potential is enough to create an arc. The detector, as fabricated, provides an output of 5 V_{dc} when an optical event occurs. Unfortunately, the field of view of the fiber optic cable is so narrow that it is extremely difficult to detect the small arc flash when contact develops. In preliminary testing, arcing was seen on the Sony monitor used for the Panasonic CCD camera, but it was not sensed by the photo detector.

IV. SAMPLE SELECTION AND PREPARATION

Rectangular coupons of aluminum and copper, 2 mm thick × 10 mm × 15 mm, were fabricated from the bulk specimens. This sample size was selected to ease handling yet still be small enough to fit within the confines of the MFT testing area. A 1 mm diameter through hole was placed near one edge of the sample coupon to allow connection of a signal lead for measuring the voltage drop across the probe–sample interface. Specimen preparation consisted of progressive wet sanding of the specimens using 600, 800, and 1200 sandpaper followed by a final polish with 0.03 μm diamond grit. Pre-testing SEM imaging of surface topography was performed to establish a baseline condition prior to frictional testing. Fig. 3 shows a steel-ball-tipped probe in contact with a copper sample. Subsequent data collection efforts will employ an atomic force microscope (AFM) to better evaluate the change in surface morphology following high current density contact.

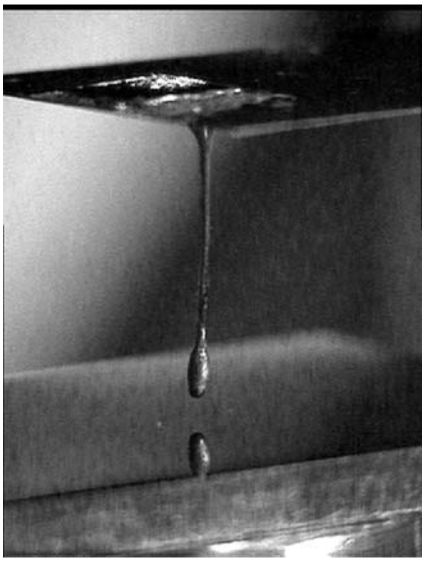

Fig. 3. Steel-ball-tipped probe nearing contact with polished surface of the sample. The laser reflecting surface is shown on top of the sensor beam.

Probe tips were fabricated from polycrystalline tungsten wire electro-chemically etched to a tip radius of approximately 250 nm. Additionally, 0.430 mm diameter steel spheres were glued to non-etched tips of tungsten wires using conductive epoxy, providing an alternate probe tip for measuring friction. It was found that the chemically etched tips would spot-weld to the sample surface, even at low-power-supply, constant current values of 0.1 A, due to the extremely high current density (> 10^{10} A/m^2) at the tip region. Switching to the probe tipped with a sphere reduced the current density sufficiently to allow for sliding contact. An image of the steel-ball-tipped probe is shown in Fig. 4.

The probe tip was brought into contact with the sample surface using a PZT stage with a 2 nm step resolution. The Physik Instremente (PI) stage is manipulated via an E-710 digital piezo controller equipped with an IEEE 488 interface to the host personal computer using commercially available data software to control stage movement. Conductive contact was verified by monitoring the resistance of the contacting surfaces using a four-wire Fluke 8522A digital multimeter. Resistance values ranged from an open-circuit condition to values of tens of ohms once contact was established.

Fig. 4. Steel ball of approximately 0.45 mm diameter mounted on end of tungsten wire using conducting epoxy.

V. VIBRATION ISOLATION

The sensitivity of the MFT cantilever beam is such that low-frequency vibrations from external sources can mask the contact force signal. The initial efforts at data collection were hampered by a persistent noise signal from external vibrations. The noise signal was found to be of two components. Room ventilation was eliminated as one of the sources by surrounding the MFT with an isolation box that prevented beam disturbance by air currents. A second component of noise was traced to a low-frequency source that was determined to originate from the cooling fan of the dc power supply. Once mounting bolts securing the PZT support Oriel stage to the air table were removed, the low-frequency input was significantly reduced. Further reduction in noise was achieved by placing a 2 mm sheet of rubber between the air table surface and the Oriel stage and by placing low-density foam sheeting between the air table surface and the legs of the dc power supply. The air table was also verified to be truly floating after performing some minor adjustments to the air leveling valves.

VI. RESULTS

The coefficient of friction in the presence of high current density was measured using the modified MFT. The probe was brought into contact with the sample surface and then translated across the surface for a distance of approximately 20 µm with constant current density conditions. A perceptible decrease in coefficient of friction was noted when comparing between conditions of constant current flow through the probe and when current was

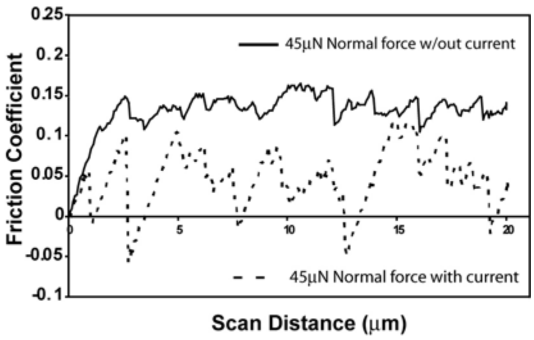

Fig. 5. Friction coefficient comparison between similar normal force (45 µN) with and without an applied constant current.

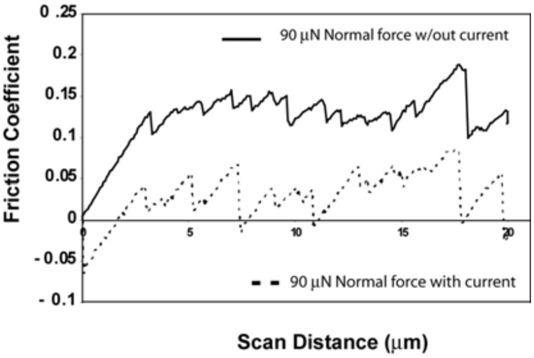

Fig. 6. Friction coefficient comparison between similar normal force (90 μN) with and without an applied constant current.

not flowing. Figs. 5–7 illustrate this observation. Although EM forces are generated within the MFT between the contact probe and the sample surface, insufficient data has been collected to speculate as to the extent of any discrepancies in force measurement due to this effect. Additional experimentation is required before a more quantitative explanation could be provided.

As expected, the coefficient of friction is relatively independent of normal force values, which for this experiment ranged from 45 μN to 110 μN, as seen in the similar coefficient of friction values for both the current and non-current cases. The periodic variation in value is speculated to be due to surface morphology causing intermittent stick-slip between probe tip and sample surface as the probe is translated. A decrease in friction coefficient with current is indicated by the dashed lines in all three figures. All other experimental conditions of sample type, current density, scan speed, and surrounding environment were held constant between the cases of constant current and no current.

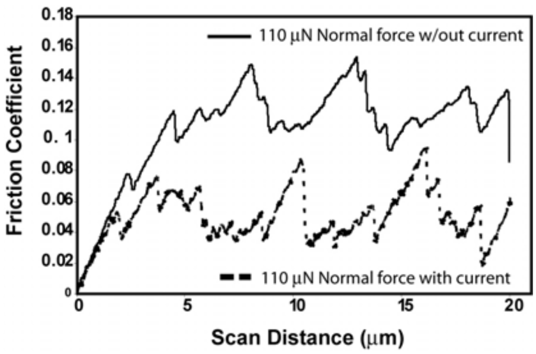

Fig. 7: Friction coefficient comparison between similar normal force (110 μN) with and without an applied constant current

VII. CONCLUSIONS AND RECOMMENDATIONS

A modified version of an MFT has been successfully used to measure coefficient of friction in the presence of electric current through the contact interface. Preliminary results indicate that current flow decreases coefficient of friction by approximately 50% in the case of metal-on-metal elastic contact with high current density (> 10^{10} A/m^2).

Further investigation is recommended for other types of contact samples and to better prepare sample surfaces to minimize surface morphology effects. Additionally, the generation of a Paschen curve for a mesoscale environment of electrical contact should be possible with the further development of a more sensitive arc detecting device.

Acknowledgment

This research is based upon work supported by the Office of Naval Research under Award No. N00014-04-1-0599. It was also supported in part by funding from the Naval Surface Warfare Center, Dahlgren Division (N0017805WR00297). Any opinions, findings, and conclusions or recommendations expressed in this publication are those of the authors and do not necessarily reflect the views of the US Navy.

References

[1] M. Wang, D. Xu, K. Ravi-Chandar, and K. Liechti, "On the development of a mesoscale friction tester," CMSSM Report Number 05-10, The University of Texas at Austin, December 2005.

[2] F. Bowden and D. Tabor, *The friction and lubrication of solids*, Oxford Press, 1964.

[3] H. Hertz, *Miscellaneous papers*, p. 146, Macmillan, 1896.

[4] E. Rabinowitz, *Friction and wear of materials*, 2nd ed., pp. 55–62, J. Wiley and Sons, 1995.